# Assessment of individual and combined gravity field solutions from Swarm GPS data and mitigation of systematic errors

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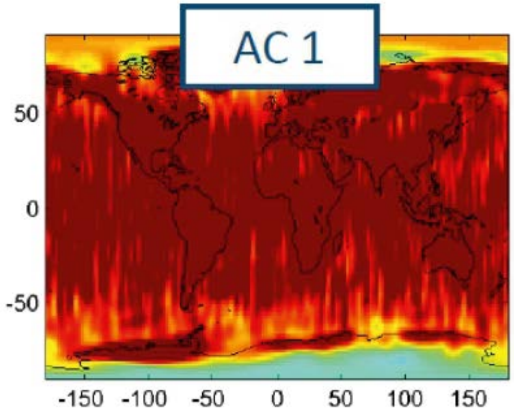
# Availability of Swarm Gravity Field Solutions

| Analysis Center | Gravity Field Solutions | |
|---|---|---|
| Astronomical Institute, University of Bern AIUB | Celestial Mechanics Approach | – AIUB KIN Orbits |
| Astronomical Institute Czech Academy of Science ASU | Accceleration Approach | – AIUB KIN Orbits<br>– IFG KIN Orbits<br>– TU Delft KIN Orbits |
| Institute of Geodesy TU Graz IFG | Short-Arc Approach | – AIUB Orbits<br>– IFG Orbits<br>– TU Delft Orbits |
| Institute of Geodesy and Geoinformation University of Bonn IGG | Short-Arc Approach | – TU Delft Orbits |

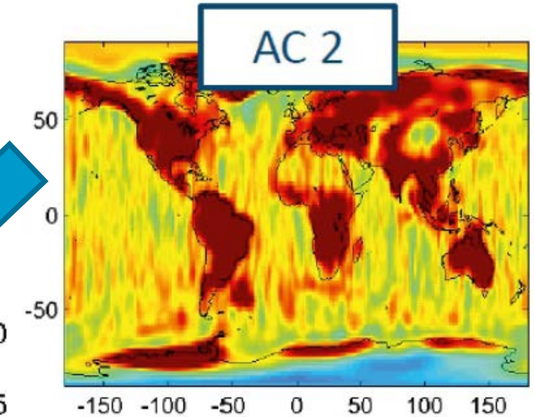
**Analysis Centers (AC) are computing monthly Swarm Gravity Field Solutions using different approaches and different GPS-based kinematic orbit solutions. Gravity Field Solutions from additional AC are expected in the near future.**

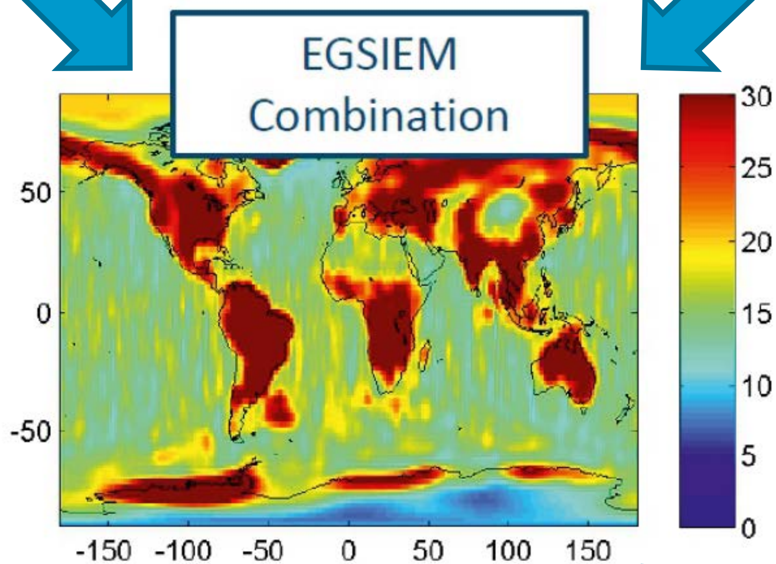
# Improving Gravity Field Solutions by Combination

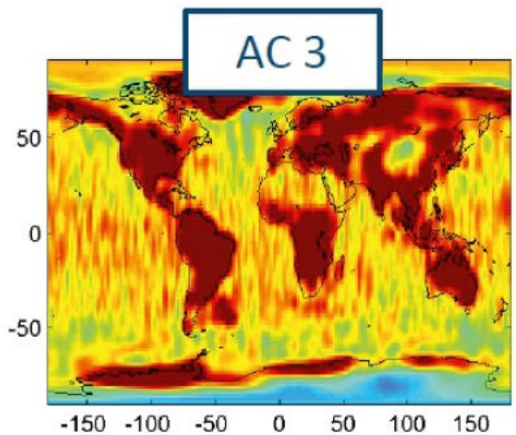


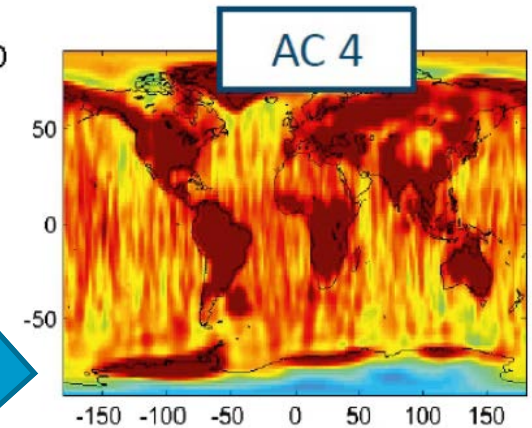

Combination Service of Time-variable Gravity Field Solutions (COST-G)

International Association of Geodesy
IAG
I G F S



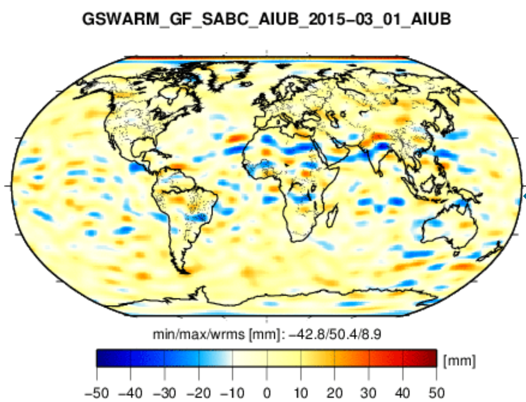



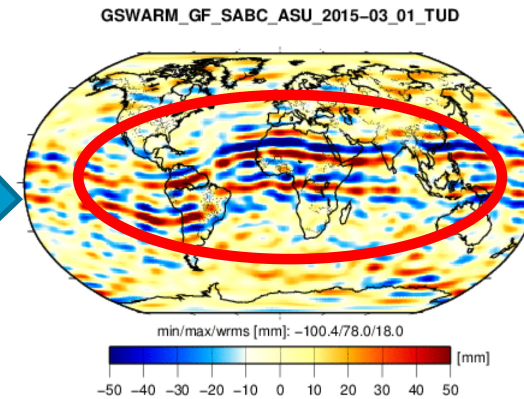




- Only one product for the user
- Reduced noise

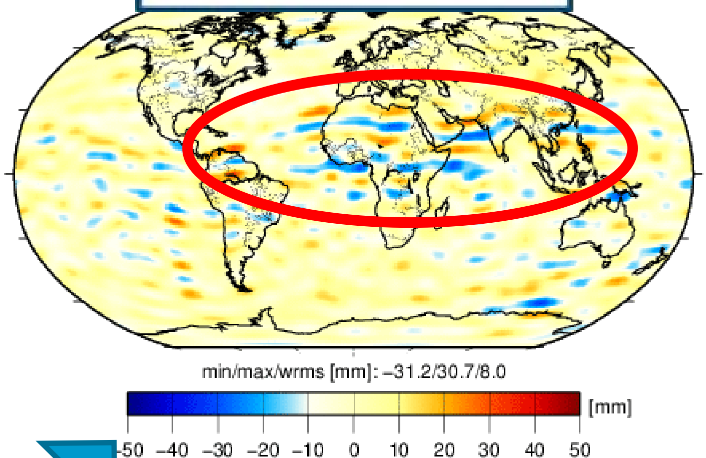
# Improving Gravity Field Solutions by Combination

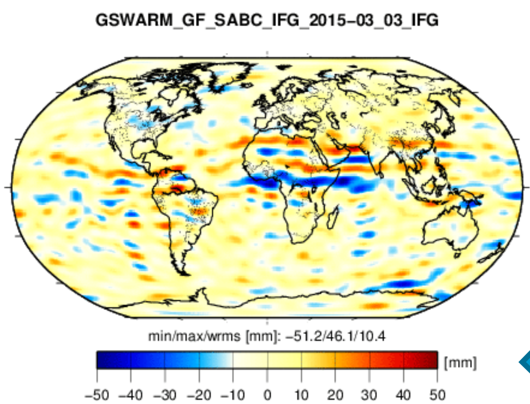



European Gravity Service for Improved Emergency Management




EGSIEM Combination




For Swarm

- not only the noise reduction is relevant (next 4 slides)
- in particular also the reduction of systematic errors (final slides)

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# Variance Component Estimation

The framework of Variance Component Estimation (VCE) is adopted to the individual gravity field solutions to compute combined solutions by a simple weighted average from *n* individual input solutions. The following explicit formulas result:

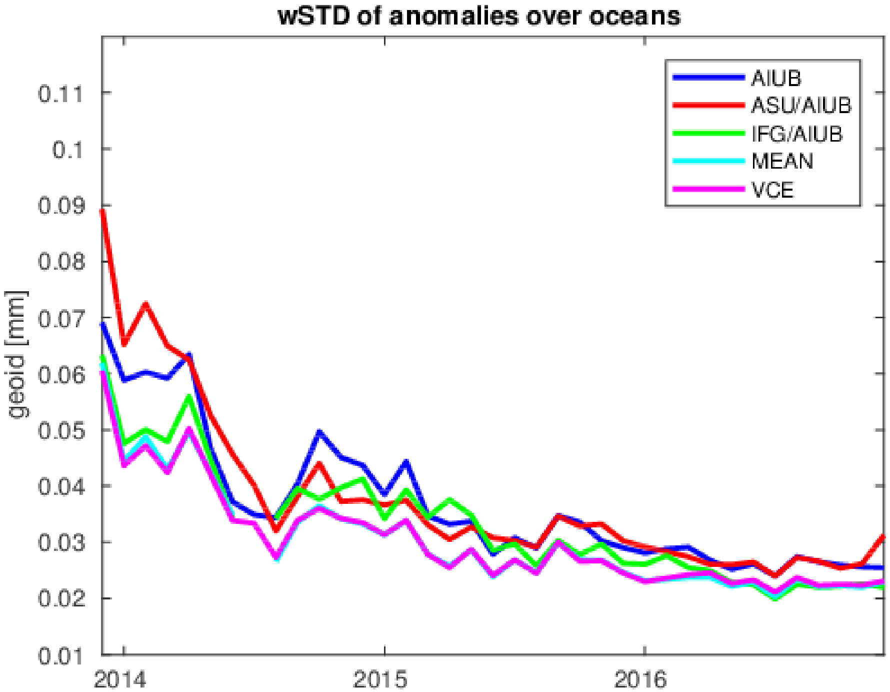
Iteration 0: $\hat{\mathbf{x}}_0 = \frac{1}{n}\sum_k \mathbf{x}_k$ with $w_{k,0} = \frac{1}{n} \quad \forall k, \ k = 1, \ldots, n$

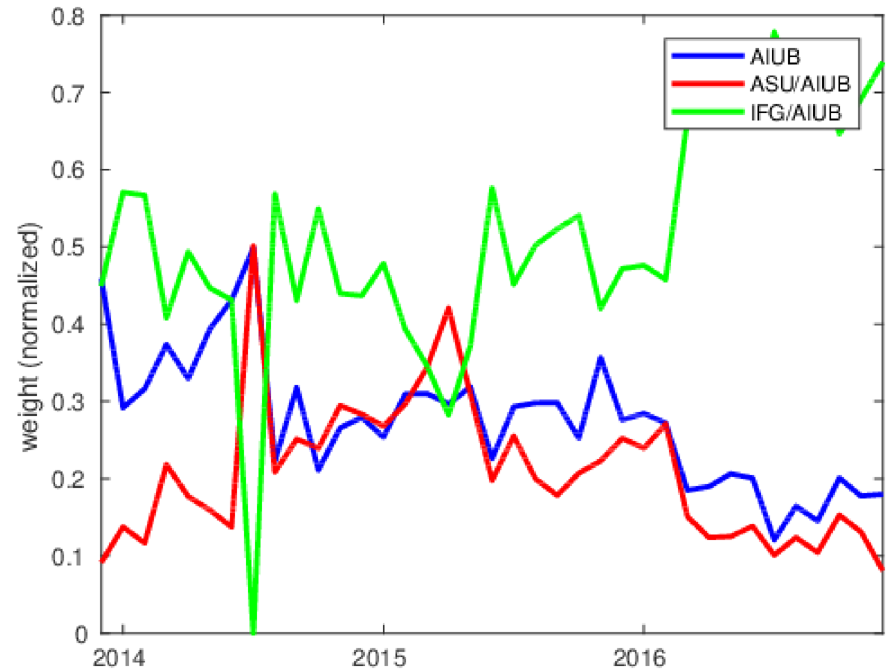
Iteration $i > 0$: $\hat{\mathbf{x}}_i = \frac{1}{\sum_k w_{k,i}} \sum_k w_{k,i}\mathbf{x}_k$ with $w_{k,i} = (1 - \frac{w_{k,i-1}}{\sum_k w_{k,i-1}}) / \mathrm{RMS}(\mathbf{d}_{k,i-1})^2$,

$\mathbf{d}_{k,i-1} = \mathbf{x}_k - \hat{\mathbf{x}}_{i-1}$ Differences to the combined solution $\hat{\mathbf{x}}_{i-1}$ from the previous iteration

Note that iteration 0 is equivalent to a simple average, iteration 1 is equivalent to the simple weighted average. Further iterations are required until the procedure converges.

# Combination: use of the same orbits

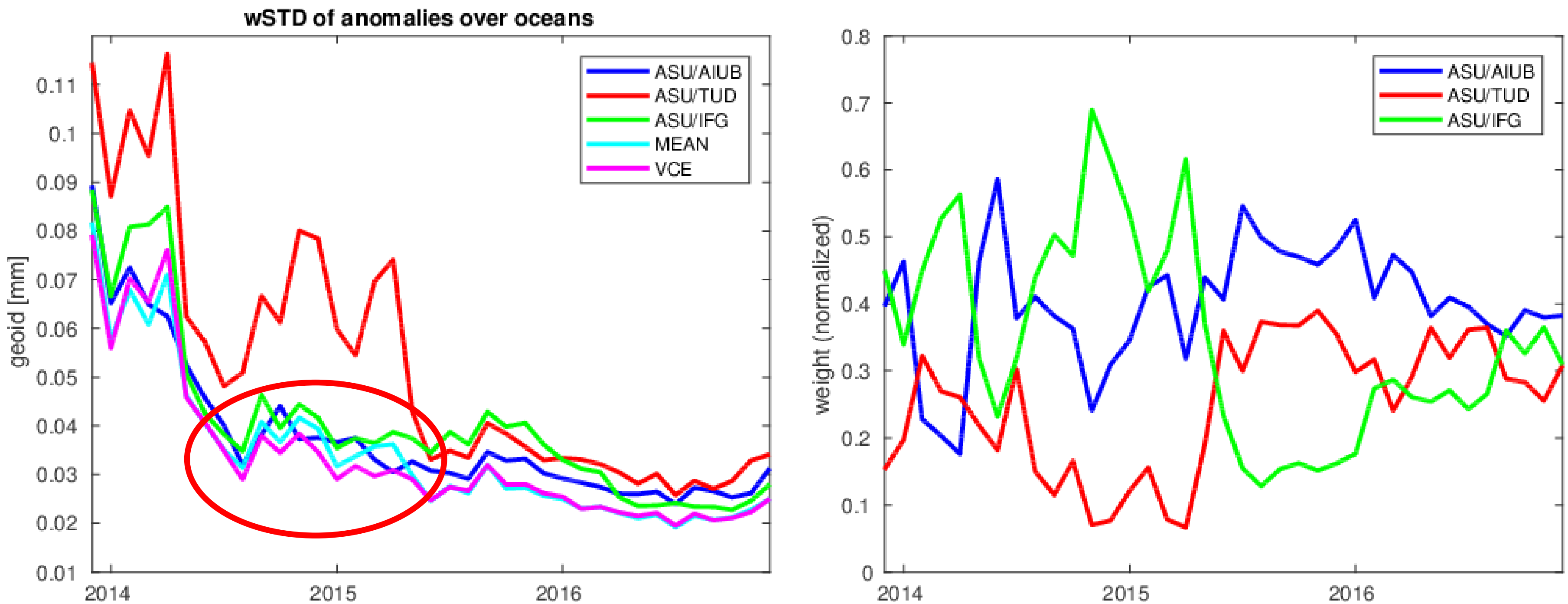



Test case: all solutions based on AIUB orbits:

- Combined solutions show lower noise than individual solutions
- Almost no difference between simple average and weighted average
- Weights suggest best performance of IfG approach

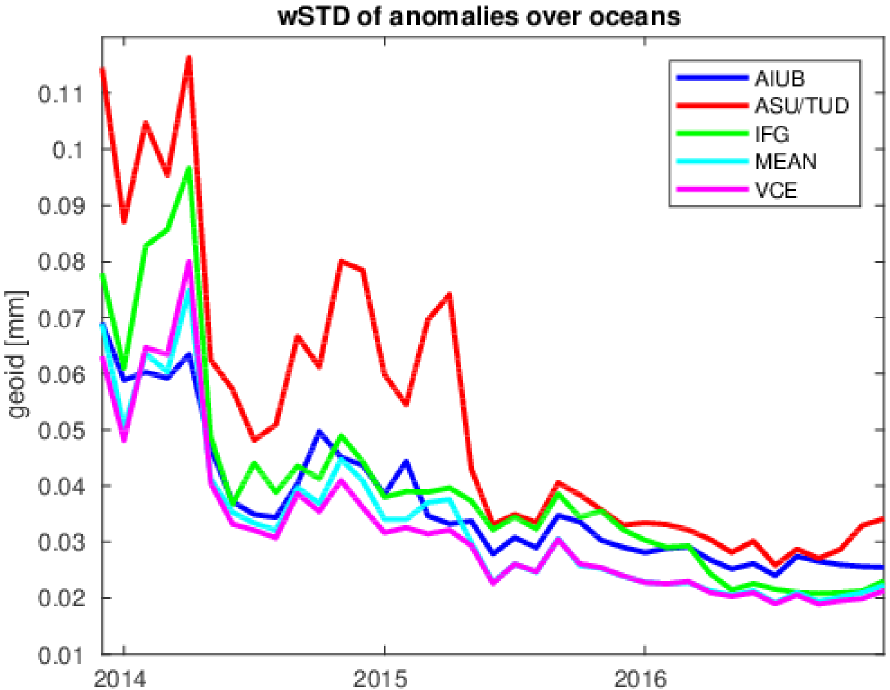
# Combination: use of the same approach




Test case: all solutions based on ASU approach:

- Orbit quality highly impacts the quality of the gravity field solutions
- Weighted average may compensate this to a certain extent
- Weights generally suggest best performance of AIUB orbits

# Combination: all input is independent





All solutions completely independent:

- Situation is a mixture of previous slides
- Combination generally performs best
- Weights suggest best performances of IfG and AIUB solutions

More information in the talk by Encarnação et al.:
Signal contents of combined monthly gravity field models derived from Swarm GPS data, Fri 13 Apr, 09:45 – 10:00, Room D1

# Mitigation of Systematic Errors: test cases

- Original GPS data
- „Standard screening“: $|dL_{gf}/dt| > 2\ cm/s$ ➔ discard GPS observation ($L_{gf}$: geometry–free linear combination)
- $|d^2L_{gf}/dt^2| > 0.025\ cm/s^2$, $|\phi| < 50°$ ➔ weight down obs. with $\sigma = 21$, as opposed to nominal $\sigma = 1$ ($\phi$: geographical latitude)
- ROTI 1: Downweight data with $\sigma = \max(ROTI \cdot 60{,}1)$
- ROTI 2: Downweight data with $\sigma = \exp(ROTI \cdot 20)$

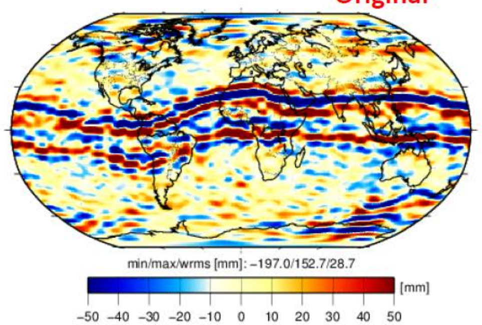
ROTI = Rate of TEC Index

$$ROTI = \sqrt{\frac{\langle \Delta TEC^2 \rangle - \langle \Delta TEC \rangle^2}{\Delta t^2}}, \quad \Delta t = 1s,\ \langle x \rangle = \text{average of } x \text{ over 31 s}$$

$$TEC = \frac{L_{gf} f_1^2 f_2^2}{40.3 m^3 s^{-2} \left(f_1^2 - f_2^2\right)} \cdot 10^{-16} \frac{TECU}{e/m^2}$$

# High Ionospheric Activity (2015/03)

Original

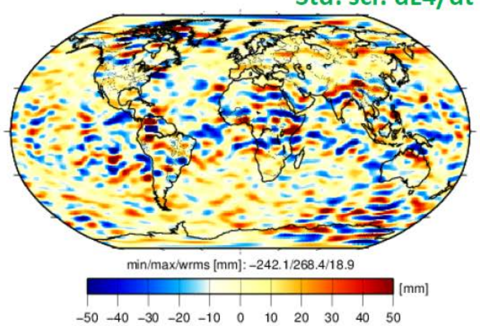



**wRMS ocean [mm]:**

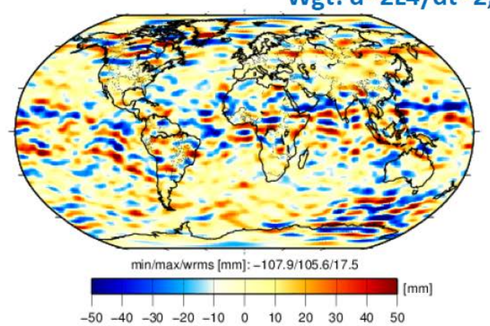
| | |
|---|---|
| au: 31.5 | |
| av: 18.6 | aw: 17.7 |
| ax: 19.5 | ay: 19.2 |

High ionospheric activity, prior to tracking loop updates

Std. scr. dL4/dt

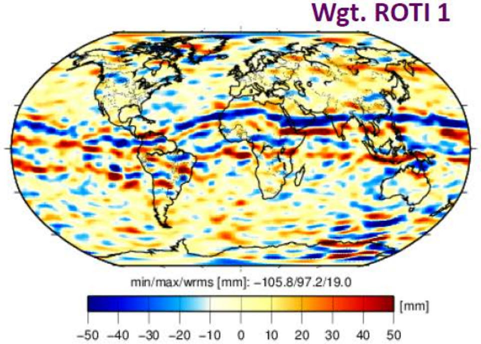



Wgt. d^2L4/dt^2, eq.

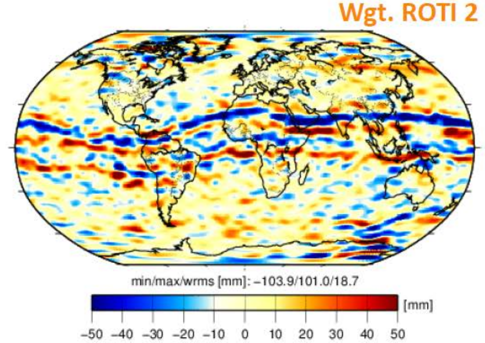



- $d^2L_{gf}/dt^2$ criterion slightly better than $dL_{gf}/dt$ criterion

Wgt. ROTI 1

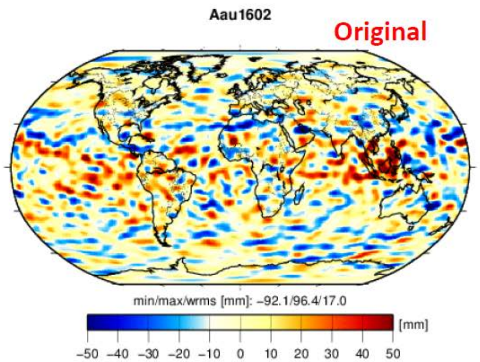



Wgt. ROTI 2




- ROTI-based weighting not as efficient to remove arte-facts along geomagnetic equator

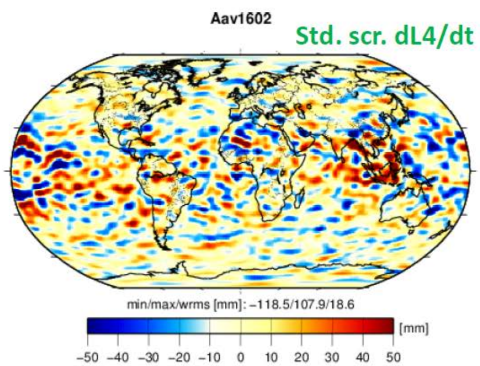
# Intermediate Ionospheric Activity (2016/02)

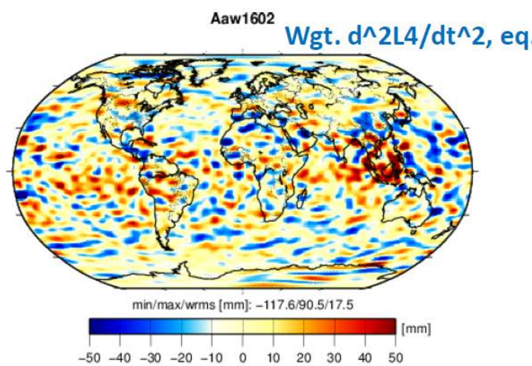



**wRMS ocean [mm]:**

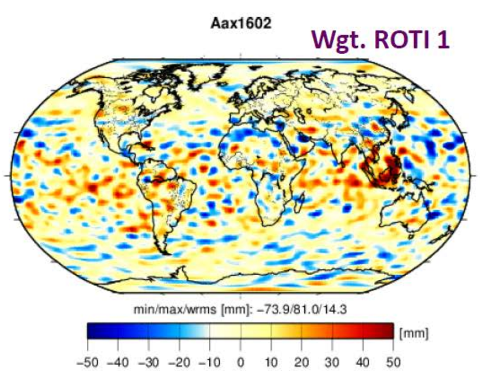
au: 17.4
av: 18.0 aw: 17.9
ax: 14.6 ay: 14.6

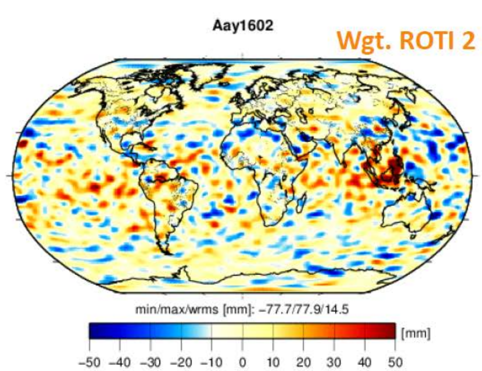
Intermediate ionospheric activity, after tracking loop updates



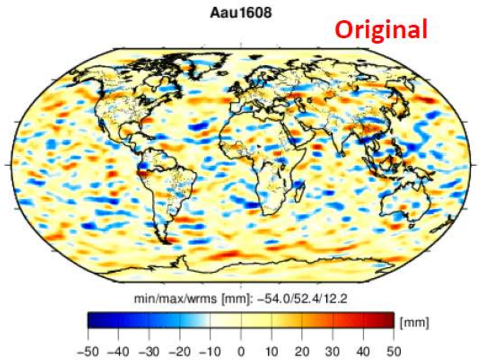

- $d^2L_{gf}/dt^2$ criterion slightly better than $dL_{gf}/dt$ criterion




- ROTI-based weighting is advantageous to reduce the noise for periods of lower ionospheric activity

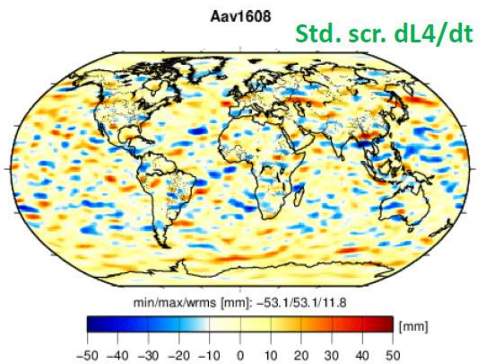
# Low Ionospheric Activity (2016/08)

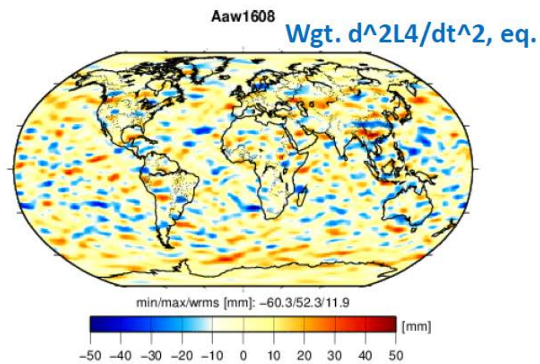


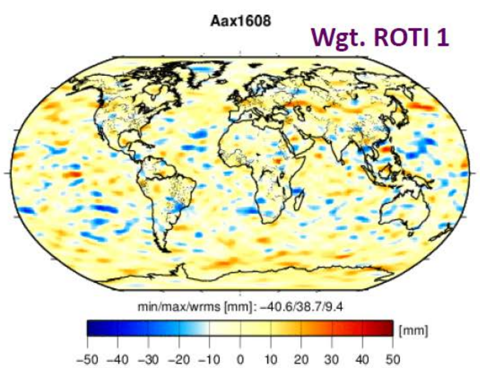

**wRMS ocean [mm]:**

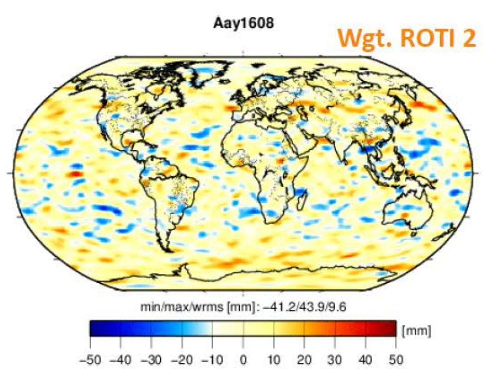
au: 12.7
av: 12.0 aw: 12.3
ax: 9.8 ay: 9.9

Low ionospheric activity,
after tracking loop updates



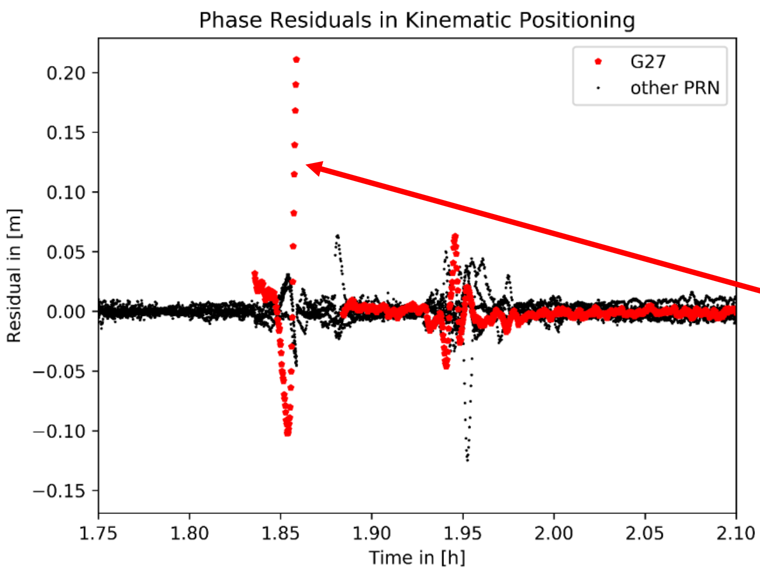



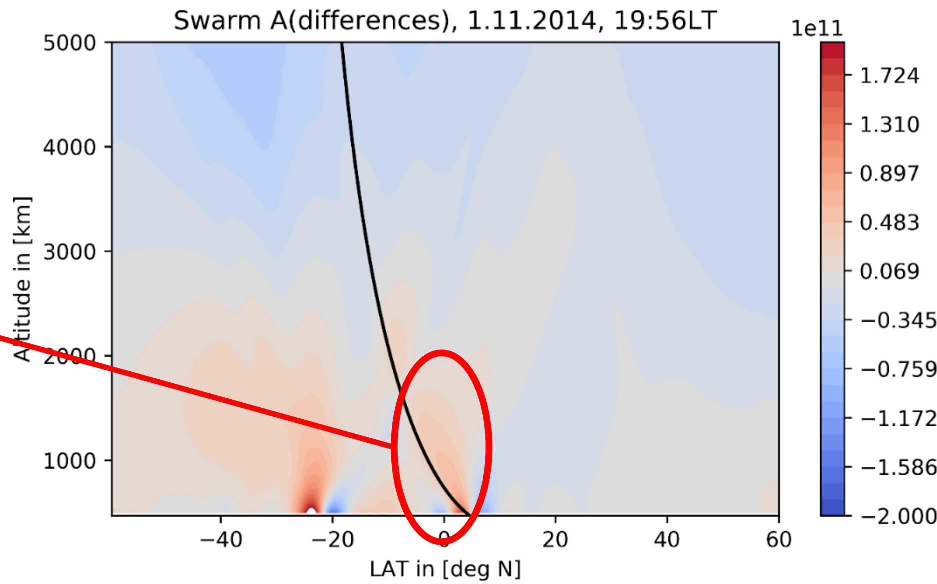




- $d^2L_{gf}/dt^2$ criterion is here slightly worse than $dL_{gf}/dt$ criterion
- ROTI-based weighting is very helpful to reduce the noise for periods of low ionospheric activity

# Impact on Ionosphere/Plasmasphere Reconstruction




Original GPS Data




Weighted GPS Data

- Swarm GPS data issues are significant for reconstruction of upper ionosphere
- Difference pattern may be related to data that were problematic for POD

More Information on the poster X4.262 by Schreiter et al.:

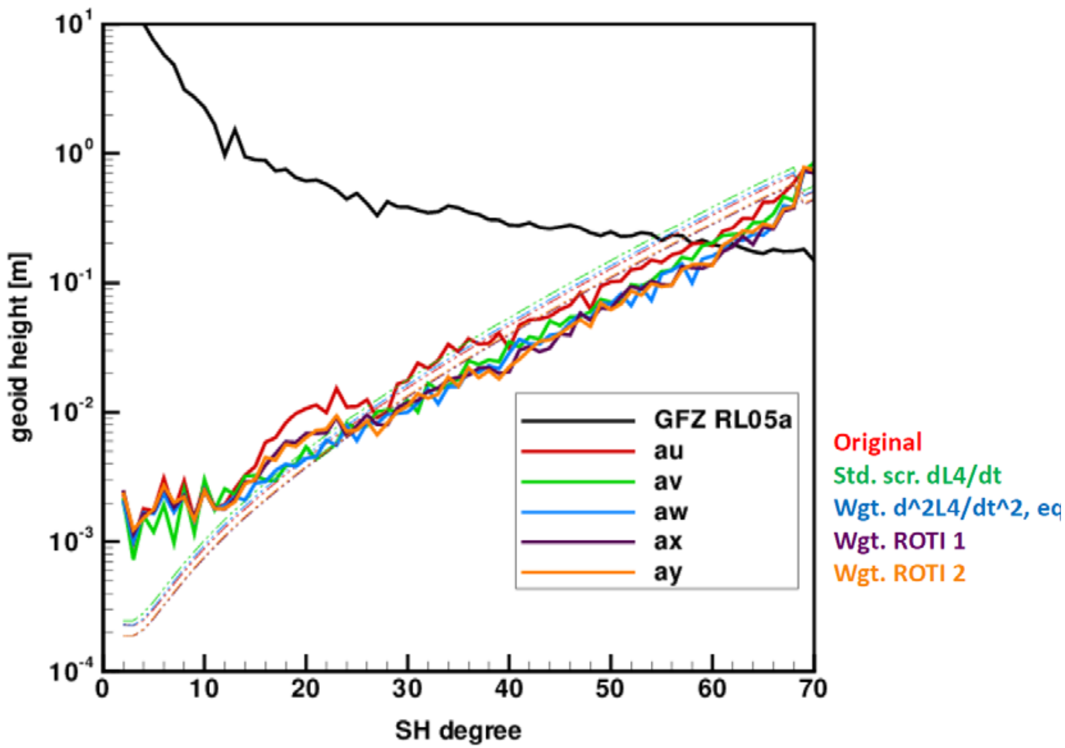
Imaging the topside ionosphere and the plasmasphere using Swarm GPS observations, Mon 09 Apr, 17:30 – 19:00, Hall X4

# Conclusion

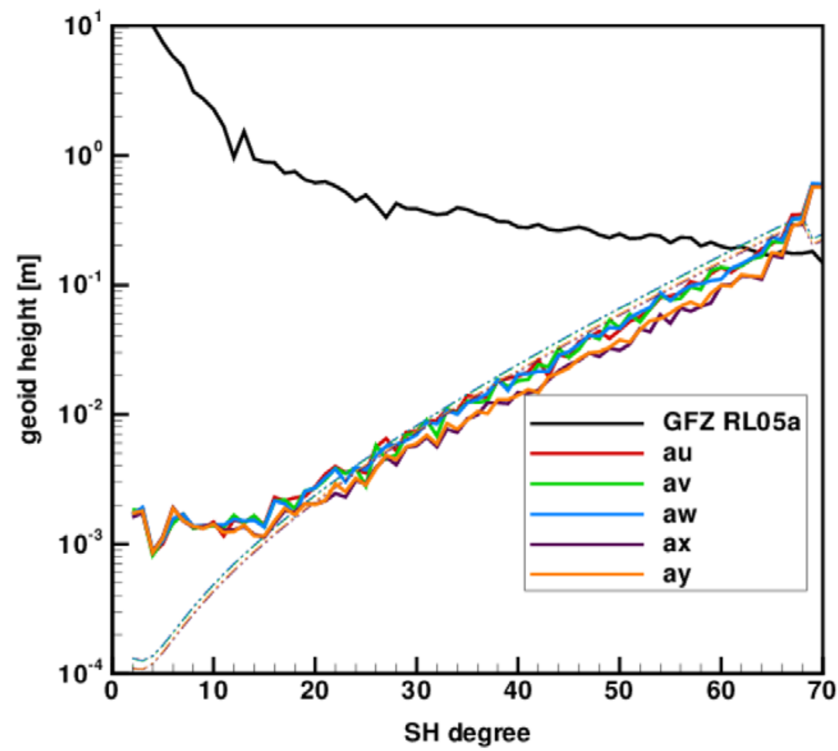
- Several analysis centers are computing Swarm monthly gravity field solutions on a regular basis.
- Combining independent gravity field solutions reduces the noise of the individual solutions.
- Systematic errors along the geomagnetic equator are affecting the Swarm solutions, especially during periods of high ionospheric activity and before the tracking loop updates.
- To remove artifacts around geomagnetic equator the ROTI-based weighting is not as efficient as the standard screening or the weighting based on $d^2L_{gf}/dt^2$ criterion.
- ROTI-based weighting significantly reduces, however, the noise, also for time periods of low ionospheric activity.
- A combination of ROTI and $d^2L_{gf}/dt^2$ based weighting seems promising to efficiently mitigate artifacts and reduce the noise.

# Difference Degree Amplitudes

### High ionospheric activity (2015/03)




### Low ionospheric activity (2016/08)




- $dL_{gf}/dt$ slightly better for low degrees
  $d^2L_{gf}/dt^2$ slightly better for higher degrees
- ROTI-based weighting is well suited to reduce the noise

Combination of ROTI-based weighting with $dL_{gf}/dt$ or $d^2L_{gf}/dt^2$ criterion might be optimal.

# SLR Validation (Swarm-A, 2015/03)

| Scenario | Red.–dynamic | | Kinematic | |
|---|---|---|---|---|
| | Mean (mm) | Std. dev. (mm) | Mean (mm) | Std. dev. (mm) |
| Original | 4.6 | 27.3 | 2.4 | 31.1 |
| Std. screening | 3.7 | 26.9 | 0.7 | 31.4 |
| $d^2L_{gf}/dt^2$ | 4.6 | 27.3 | 1.9 | 32.5 |
| ROTI 1 | 4.9 | 26.5 | 1.0 | 28.8 |
| ROTI 2 | 5.0 | 25.8 | 0.9 | 28.7 |

**SLR observations of Graz, Greenbelt, Haleakala, Hartebeesthoek, Herstmonceux, Matera, Mount Stromlo, Potsdam, Wettzell (SOSW), Wettzell (WLRS), Yarragadee, and Zimmerwald, 20cm outlier threshold, 10°elevation cutoff.**

# SLR Validation (Swarm-A, 2016/02)

| Scenario | Red.–dynamic | | Kinematic | |
|---|---|---|---|---|
| | Mean (mm) | Std. dev. (mm) | Mean (mm) | Std. dev. (mm) |
| Original | 8.4 | 12.1 | 6.4 | 16.5 |
| Std. screening | 8.1 | 13.1 | 6.3 | 22.9 |
| $d^2L_{gf}/dt^2$ | 8.4 | 12.1 | 6.1 | 16.0 |
| ROTI 1 | 8.5 | 12.5 | 5.7 | 15.4 |
| ROTI 2 | 8.5 | 12.6 | 5.9 | 15.5 |

**SLR observations of Graz, Greenbelt, Haleakala, Hartebeesthoek, Herstmonceux, Matera, Mount Stromlo, Potsdam, Wettzell (SOSW), Wettzell (WLRS), Yarragadee, and Zimmerwald, 20cm outlier threshold, 10°elevation cutoff.**

# SLR Validation (Swarm-A, 2016/08)

| Scenario | Red.−dynamic | | Kinematic | |
|---|---|---|---|---|
| | Mean (mm) | Std. dev. (mm) | Mean (mm) | Std. dev. (mm) |
| Original | 4.9 | 14.2 | 3.9 | 16.6 |
| Std. screening | 5.0 | 14.3 | 3.9 | 16.7 |
| $d^2L_{gf}/dt^2$ | 4.9 | 14.2 | 3.9 | 16.8 |
| ROTI 1 | 4.7 | 14.7 | 3.8 | 17.0 |
| ROTI 2 | 4.7 | 14.7 | 3.8 | 16.9 |

**SLR observations of Graz, Greenbelt, Haleakala, Hartebeesthoek, Herstmonceux, Matera, Mount Stromlo, Potsdam, Wettzell (SOSW), Wettzell (WLRS), Yarragadee, and Zimmerwald, 20cm outlier threshold, 10°elevation cutoff.**